2HDM with Soft CP-violation Confronting EDM Constraints

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1. Introduction

CP-violation: discovered in meson sector. Other possible effects may appear as:
- Electric dipole moments (EDM, for e, n, etc.);
- Collider phenomenology.
Here we mainly discuss the EDM effects.
Theoretically: a typical type of new physics, also motivated by baryon asymmetry, may appear in models with extended scalar sector — choose two-Higgs-doublet model (2HDM) as example.

2. Model Set-up

2HDM with soft broken \( Z_2 \) symmetry:

- \( V = \frac{\lambda_3}{2} \left( \phi_1^* \phi_1 \right)^2 + \frac{\lambda_2}{2} \left( \phi_2^* \phi_2 \right)^2 + \lambda \phi_1^* \phi_2 \phi_1 \phi_2 + \frac{\lambda_2}{2} \left( \phi_1^* \phi_2 \right)^2 + \text{H.c.} \)
- \( m_{\tau_2}^2 = m_{\phi_1^* \phi_1}^2 - \lambda \phi_1 \phi_2 \)
- Doublets: \( \phi_{1,2} \equiv \left( \phi_{1,2}^+, \phi_{1,2}^0 + \phi_{1,2}^+ \phi_{1,2}^0 \right) \), and define \( \phi \equiv \phi_{1,2}/v_{1,2} \) usual.
- Nonzero \( m_{\phi_1}^2 \) soft breaks the \( Z_2 \) symmetry.
- \( \lambda_{1,2,3} \) and \( m_{\phi_1}^2 \) are real, \( \lambda \) and \( m_{\phi_2}^2 \) can be complex; we can always put \( \phi_{1,2}/v_{1,2} \) real.
- Condition: \( \Im \left( m_{\phi_1}^2 \right) = m_1 v_1 \lambda (\text{real}), \) and thus complex \( \lambda \) and \( m_{\phi_2}^2 \) mean CP-violation.

In CP-violation case, neutral scalars mixing:

- \( (H_1, H_2, H_3) \) ≃ \( (\phi_{1,2}/v_{1,2}, \chi_{1,2} \lambda^2 \chi_{1,2}^* \chi_{1,2}^0, \eta_{1,2}/v_{1,2}) \) can couple to only one Higgs doublet. Four types:
- \( T_1, T_2, T_3, T_4 \)

Interaction in mass eigenstates:

- \( \sum_{i} C_{ij}^2 H_i \)
- \( \sum_{j} m_j \left( c_{ij} H_1 f_j + H_1 \right) + \text{H.c.} \)

3. EDM Constraint

- Operators: \( \bar{e}_L e_R \phi, \bar{e}_L \bar{e}_R \phi \), \( \bar{e}_L \bar{e}_R \sigma \phi \), \( \bar{e}_L \bar{e}_R \phi \)
- Both violate CP, operator corresponding to e-N interaction also affect on observed EDM.
- Current: \( |d_{eN}| = |d_{eN}| < 1.1 \times 10^{-29} \) e·cm at 90% C.L., \( k = 1.6 \times 10^{-22} \) TeV²·e·cm for \( \text{TlO} \) [ACME, nature 362, 355 (2018)].

4. nEDM Constraint

- Current: \( |d_n| < 3.0 \times 10^{-26} \) e·cm at 90% C.L. [C. A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006); and later updates.]

Calculation: three kinds of operators:

- QCD running from weak scale to hadron scale, and QCD sum-rule estimation at hadron scale.

5. Future nEDM

- Usually the sensitivity of e EDM is better than n EDM, but as shown above, in some models as Type II and III, cancelation in e EDM would weaken the constraints on CP-phases in Higgs-fermion couplings.
- n EDM can be a good supplement to set further limit on CP-phases in Higgs-fermion couplings.

An example — nEDM @ PSI: accuracy is expected to reach \( \delta d_n \approx 10^{-27} \) e·cm [C. Abel et al., arXiv: 1811.02340; etc.]

- If nothing nonzero appears, we can set \( |d_n|^2 \approx 5.3 \times 10^{-29} \), \( |d_{eN}| \lesssim 5.3 \times 10^{-29} \).
- Else nonzero evidence will appear in n EDM.
- Also cross check to collider tests.

6. Summary and Discussion

We discuss the EDM constraints using the widely studied 2HDM with soft CP-violation as an example, all the four types of Yukawa interactions are included in our analysis:
- Type I & IV models are strictly constrained by e EDM; the CP-phases \( \arg(c_{1f}) < 1 \times 10^{-4} \) thus we do not discuss these two types further.
- Type II & III models can behave cancelation in narrow region; we discuss the scenario with free \( \alpha_2 \) but without \( |s_2\alpha_2| \approx 1 \), thus \( m_2 \) are close to each other.
- The e EDM behavior are similar for Type II and III models, the only difference comes from e-N interaction term.
- In cancelation region, \( \alpha_2 \) can not be limited by e EDM, but for Type II model, it is limited by n EDM as \( |\alpha_2| \lesssim 0.14 \).
- For Type III model, \( \alpha_2 \) is also not limited by n EDM, but it can be limited by Higgs signal strengths global fit as \( \alpha_2 \lesssim 0.27 \).

We also discuss the importance of future measurements on n EDM with better accuracy:
- n EDM measurement with \( \delta d_n \approx 10^{-27} \) e·cm can set constraint on \( \alpha_2 \) to \( \text{O}(10^{-4.5}) \), for both Type II and III models, if nothing seen.
- For models with cancelation in e EDM, first evidence may appear in n EDM measurement, thus n EDM is more effective than e EDM in cases CP-violation is hidden behind e EDM.
- n EDM with better accuracy may also be cross checks with collider tests on CP-violation.